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Carrier-concentration dependence of critical superconducting current induced by the proximity effect in silicon

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The carrier-concentration dependence of the critical superconducting current induced by the proximity effect in a heavily B-doped Si has been studied experimentally. It is found that the critical current which flows through the *p*-type-Si–coupled junction can be controlled both by the acceptor concentration and by the induced carrier concentration by the electric potential applied to the gate electrode.

In a normal metal backed with a superconductor, superconducting electron pairs are well known to be induced by the superconducting proximity effect.[1] Superconductor–normal-metal–superconductor (S-N-S) junctions have been used to study the superconductivity induced by the proximity effect.[2–4] Recently, semiconductor-coupled S-N-S junctions with a coplanar structure have also been developed employing microfabrication techniques.[5–8] In such junctions, heavily doped semiconductors serve as normal metals.

Employing a semiconductor instead of a normal metal in the S-N-S structure, it is possible to change the carrier concentration in the semiconductor affected by the proximity effect. Besides the dopant concentration, we can control the carrier concentration in the semiconductor by applying an electric potential to a suitably arranged gate electrode. Therefore, we can control the critical superconducting current which flows through the semiconductor-coupled junction by the applied electric potential. This idea of a gate-controlled superconducting field-effect transistor was proposed by Clark several years ago.[9] However, the gate-controlled operation has not been achieved until recently.

In our previous work[10] we reported the first experimental observation of the voltage control of the critical superconducting current in a *p*-type-Si–coupled junction which had a metal-oxide-semiconductor– (MOS–) type structure with submicron spacing electrode. Takayanagi and Kawakami[11] have also reported a similar result for a metal-insulator-semiconductor– (MIS–) type structure which used the surface inversion layer of InAs as the coupling semiconductor. However, due to the high surface-state density, the sensitivity of the voltage modulation was very low in their sample, and it has not yet been analyzed clearly how the applied voltage controls the critical superconducting current.

In this Rapid Communication, we first describe the relation between the critical superconducting current and the doping concentration in a submicron spacing planar *p*-type-silicon–coupled junction without gate electrode. Secondly, with a MOS–type structure, the influences of the carrier density modulation by the electric potential on the critical superconducting current are investigated.

The first type of our semiconductor-coupled junctions has the same structure as reported by Ruby and Van Duzer.[7] The substrate was a (100)-oriented Si wafer, and boron was heavily doped on the surface of the substrate at a concentration of 5×10^{18} to 5×10^{20} cm^{-3}. The Pb–12-wt.% In–4-wt.% Au alloy film with the thickness of 180 nm was deposited on the Si wafer for superconducting electrodes. The critical temperature of the superconducting film was 6.9 K. The electrode pattern of the width of 20 μm was formed by an Ar-ion etching technique using a photoresist mask. The submicron spacing between the two superconducting electrodes was fabricated by means of electron beam lithography and Ar-ion etching techniques.

Because the electrical characteristics of semiconductor-coupled junctions depend on the surface condition of the semiconductor substrate, especially on the surface treatment before the deposition of the superconducting metal, the Si wafer was carefully cleaned in the same manner as reported by Ruby and Van Duzer.[7]

In order to check if our junction can act as a semiconductor-coupled junction at 4.2 K, we first investigated the relation between the critical superconducting current, I_c, and the spacing between superconducting electrodes, L. The results are shown in Fig. 1. The spacing L was measured at room temperature using a scanning electron microscope after the electrical characteristics were measured at

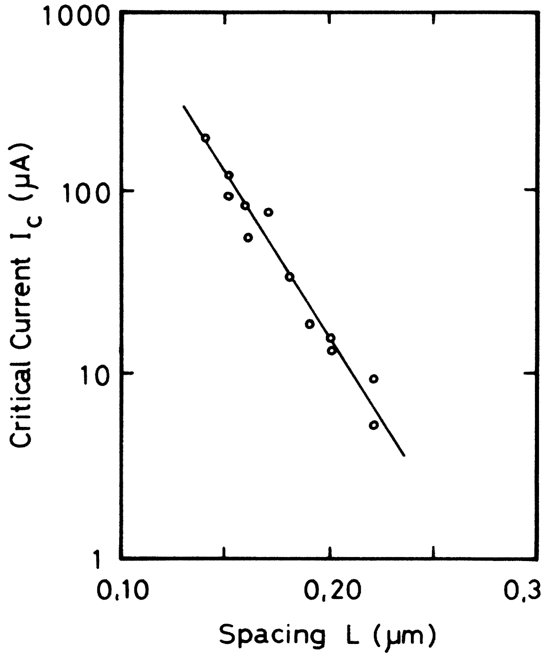

FIG. 1. Dependence of the spacing between two superconducting electrodes L on the critical superconducting current I_c. The solid line is the numerical result calculated from Eq. (1). The boron concentration was 3×10^{19} cm^{-3}.

low temperatures. The boron concentration was determined to be $(3 \pm 0.5) \times 10^{19}$ cm^{-3} by means of secondary-ion mass spectroscopy (SIMS). For the junctions with the spacing L smaller than 0.2 μm, the critical superconducting current was obtained. Typical $I_c R_n$ products were from 0.4 to 0.8 mV at 4.2 K, where I_c and R_n were the critical superconducting current and the normal resistance, respectively.

The temperature dependence of the critical superconducting current was also measured, and the result is shown in Fig. 2. The spacing between the two superconducting electrodes and the boron concentration in the Si single crystal were 0.17 μm and 3×10^{19} cm^{-3}, respectively.

In Figs. 1 and 2, the solid line represents the numerical result calculated by the following equation[6,7] being based upon the proximity effect theory,

$$I_c \propto \Delta_n(T)^2(1/\xi_n)[\cosh^2(L/2\xi_n)]^{-1} \ , \tag{1}$$

where $\Delta_n(T)$ is the induced pair potential of the normal metal at S/N boundary, L is the spacing between two superconducting electrodes, and ξ_n is the coherence length in the normal metal. Semiconductors have been treated as dirty materials.[12] At the dirty limit, ξ_n can be written[1] as

$$\xi_n(T) = (\hbar D/2\pi k_B T)^{1/2} \ , \tag{2}$$

where D is the electron diffusion constant in the normal metal. Seto and Van Duzer[6] derived the expression of ξ_n for semiconductor-coupled junctions as follows:

$$\xi_n(T) = (\hbar^3 \mu/6\pi k_B T e m^*)^{1/2}(3\pi^2 n)^{1/3} \ , \tag{3}$$

where m^* is the carrier effective mass, μ is the carrier mobility, and n is the carrier density for the semiconductor. In this expression, a three-dimensionai free-electron model is assumed and the term $n^{1/3}$ originates from this assumption. In Fig. 1, the best match was obtained by setting ξ_n to be 11 nm. This value agrees fairly well with the result of 13 nm obtained from Eq. (3) assuming the hole mobility in Si to be 100 cm^2/V s.[13] The numerical results obtained by Eqs. (1) and (3) are in good agreement with the experimental data shown in Figs. 1 and 2.

The critical superconducting currents in the p-type-Si–coupled junctions with various boron concentrations are shown in Fig. 3. The spacing L of junctions is chosen to be 0.15 ± 0.01 μm, and the current I–voltage V characteristics were measured at 4.2 K. Because direct measurements of the carrier concentration n were not made, we analyzed I_c assuming that the carrier concentration n is proportional to boron concentration N_a because the value of N_a is restricted within the small range from 10^{19} to 10^{20} cm^{-3}.

From Eqs. (1) and (3), it is derived that the value of $\ln(I_c)$ depends on the carrier concentration n as $(\frac{1}{3})\ln(n) - (L/C)n^{-1/3}$, where factor C changes with temperature.[6,7] For the value of L larger than 0.15 μm, the first term changes rather slowly with the increase of n. Therefore the second term becomes dominant.

The term $n^{-1/3}$ originates from the free-electron-gas model assumed in Seto and Van Duzer's theory.[6] This model should be verified by the measurement of the characteristics of semiconductor-coupled junctions. The dimensionality of the electron system in the semiconductor can be tested from the linearity between $\ln(I_c)$ and $n^{-1/3}$. In Fig. 3, $\ln(I_c)$ and $n^{-1/3}$ show a linear relation. Therefore, it is concluded that the carrier concentration dependence of I_c for the junction in which a p-type Si is used as semiconductor can well be explained by a three-dimensional free electron model. This result is different from the two-

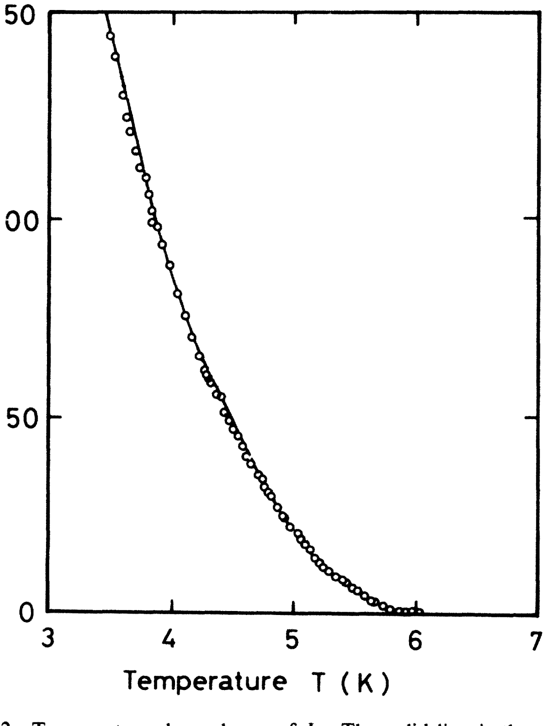

FIG. 2. Temperature dependence of I_c. The solid line is the numerical result calculated from Eq. (1). The spacing L and the boron concentration were 0.17 μm and 3×10^{19} cm^{-3}, respectively.

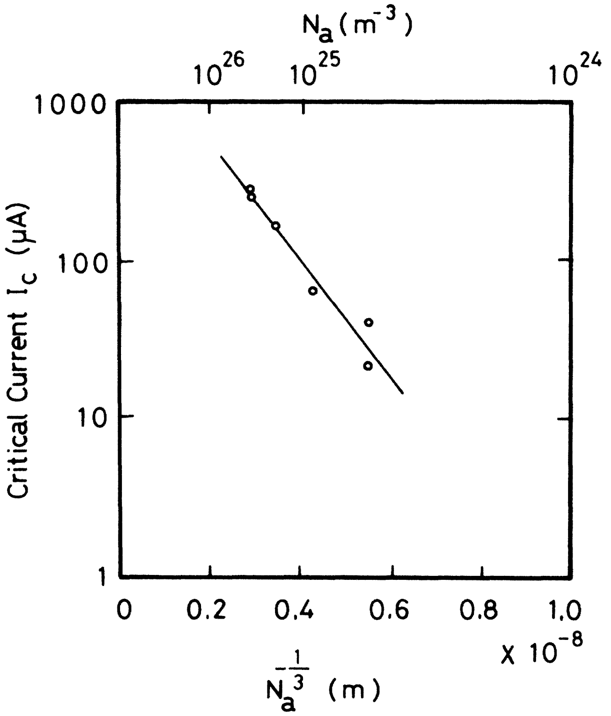

FIG. 3. The relationship between boron impurity concentration N_a and critical superconducting current I_c at 4.2 K. The solid line is the n-dependent part of Eq. (1). The spacing L is 0.15 ± 0.01 μm.

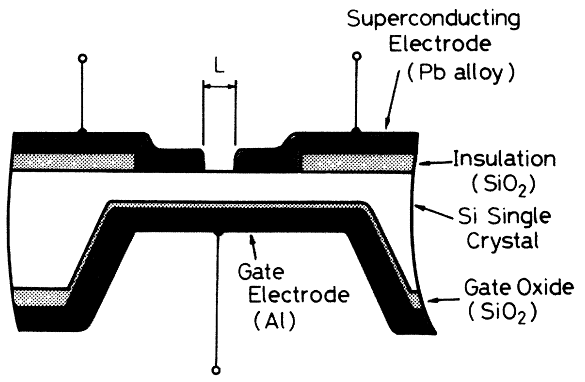

FIG. 4. Schematic cross section of the junction with an oxide-insulated gate electrode.

dimensional electron gas system obtained for the surface inversion layer of p-type InAs by Takayanagi and Kawakami.[11] The reason for this difference may be that the p-Si layer in this work was thicker than the inversion layer of p-InAs.

To study the voltage control of the superconducting current, junctions with an oxide-insulated gate electrode, as shown in Fig. 4, were fabricated. A p-type Si single-crystal film was used as the semiconductor in the junction. The Si thin film with an area of 400×400 μm^2 was obtained by anisotropically etching the undoped region (from the back side) of a (100)-oriented Si wafer. The thickness of the Si film was about 100 nm. A gate oxide with a thickness of 40 nm was formed by the dry oxidation of this thin Si film. The thickness of the remaining Si film was about 70 nm. An Al gate electrode of a thickness of 700 nm was formed on the gate oxide of SiO$_2$. Two superconducting electrodes were formed by the same method as for the first- type junction. The spacing between the two superconducting electrodes was about 0.2 μm. The boron concentration in Si was measured to be 5×10^{18} cm^{-3} by means of SIMS.

The critical superconducting current I_c between the two superconducting electrodes was less than 5 μA for zero gate voltage. However, an applied gate voltage of more than -50 mV caused I_c to increase. The relationship between the observed critical superconducting current and the applied gate bias voltage was plotted in Fig. 5.

The negative gate voltage causes an accumulation of carriers in the semiconductor, and makes the carrier density increase. Assuming that the accumulated carrier concentration n is uniform and proportional to the applied gate voltage V_g, we can calculate I_c with respect to $1/V_g$ using Eqs. (1) and (3). The numerical result is represented by a solid line in Fig. 5. The result is fitted to the experimental plots at $V_g = -0.1$ V. The numerical results are in reasonable agreement with the experimental ones for small values of V_g. For values of V_g larger than 150 mV, however, experimental values begin to deviate from the numerical ones. The actual carrier concentration n has a distribution in the semiconductor, and it is not yet clear how this distribution of n is related to the coherence length in the semiconductor ξ_n. Moreover, the presence of an electric potential in the semiconductor would affect the critical superconducting current. Such an effect, which was not taken into account in Seto and Van Duzer's theory,[6] would explain the disagreement of the theoretical values with the experimental ones in the high-gate-voltage region. In order to obtain more detailed information of the relation between ξ_n and electric potential, and of the induced pair potential in the semiconductor, it becomes necessary to measure the proximity effect tunneling[14] in our semiconductor-coupled junctions when an electric potential is applied.

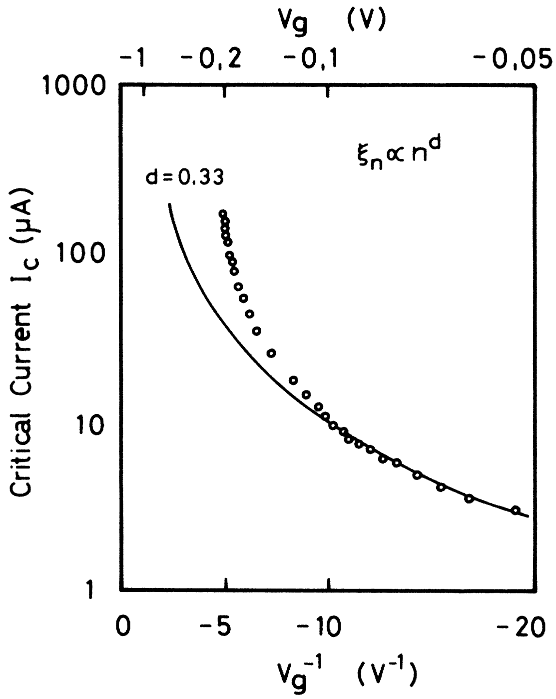

FIG. 5. The relationship between the applied gate-bias voltage and the observed critical superconducting current. The measurement was made at 4.2 K.

In summary, the carrier concentration dependence of the critical superconducting current in a semiconductor (p-type Si)-coupled junction was investigated. It was found that the coherence length, ξ_n, in the p-type Si depended on the carrier concentration n in such a manner as $\xi_n \propto n^{1/3}$, and that the field-induced change in the carrier concentration affects the critical superconducting current in a semiconductor-coupled junction. The superconductor-semiconductor junction, both when an electric potential is applied and when field-induced carriers exist, will provide us with further information about the superconductivity which is induced by a proximity effect in the semiconductor.

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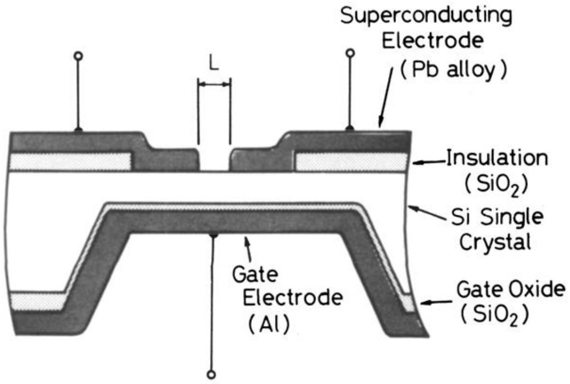

FIG. 4. Schematic cross section of the junction with an oxide-insulated gate electrode.